

## Modeling the origin of astrophysical jets from galactic and extra-galactic sources

*A New approach to combine the accretion-wind topologies*

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**Abstract.** Astrophysical jets are physical conduits along which mass, momentum, energy and magnetic flux are channeled from the stellar, galactic and extra-galactic objects to the outer medium. Geometrically these jets are narrow (small opening angle) conical or cylindrical/semi-cylindrical protrusions covering an astonishing range in size. While the jets associated with young stars are typically  $10^{17}$  cm in length, jets from some giant extra-galactic sources have an overall extent in excess of  $10^{24}$  cm [1]. Thus the jet phenomenon is seen on scales that cover more than seven orders of magnitude and some of the extra-galactic radio jets are considered to be the largest single coherent structure found in the universe. Though it is now a well-known fact that a variety of celestial objects, spanning from stars (having all masses) during their formation (Young Stellar Objects) to Active Galactic Nuclei (and possibly sources of  $\gamma$  ray bursts also [2]) suffer mass loss through jets, the detailed nature of the origin of the extragalactic jets is not quite clear due to the lack of proper understanding of the underlying physical mechanism responsible for jet production. In this article efforts have been made to justify the validity of a model very recently proposed by us, which, for the first time we believe, is able to explain the formation of extragalactic cosmic jets using a self-consistent inflow-outflow system. Primarily intended to make intelligible to readership not working exclusively in this field, the philosophy behind the subject is essentially emphasized in this article instead of providing the mathematical details. This article, thus, is absolutely freed from a single mathematical equation/formula. Readers interested to delve into the technical details are suggested to go through the references cited at appropriate places.

**Keywords :** Jets, outflows, black holes

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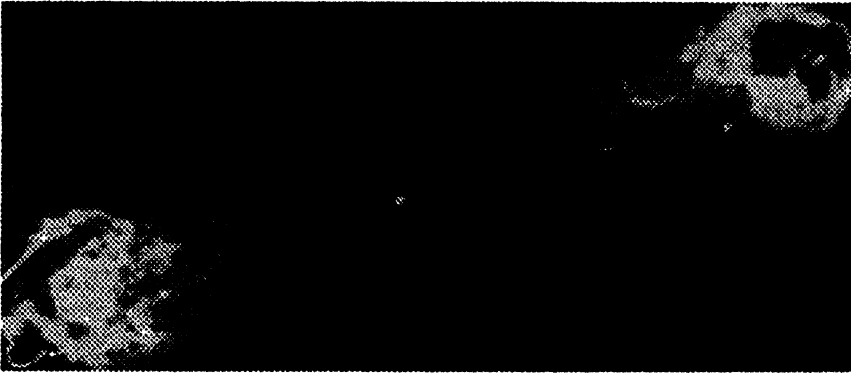


Figure 1: VLA radio image of Cygnas A after repeated correction from atmospheric effects and calibration errors (Observation by R. H. Perley and J. W. Dreher). The bright spot in the center is the core of the galaxy. Two bright patches on either side of the core (one at the top right and the other at the lower left corner of the image) represent the radio emitting lobes while the thin band connecting the central spot with the top right patch is the jet shooting out from the core (Reproduced with kind permission from R. H. Perley and J. W. Dreher)

## 1. Introduction

One of the most prominent signatures of activities around the Active Galactic Nuclei (AGN) <sup>1</sup> is the presence of mass outflows and jets. AGNs produce cosmic jets through which immense amount of matter and energy are ejected out of the cores of the galaxies [3]. The structure of these jets can reach sizes of several million light years and extent way beyond their host galaxies into the vastness of intergalactic space. Similarly, micro quasars <sup>2</sup> have also been very recently discovered where the mass outflows are formed from stellar mass black hole candidates [4].

Looking back at the era of infancy of radio observations of the extragalactic

<sup>1</sup>'Active' galaxies are distinguished from ordinary galaxies in that they show indications of having energy output not related to ordinary stellar processes (standard thermonuclear evolution of energy). Their 'activity' is centered in a small nuclear region ( $R \ll 1 \text{ pc} \sim 3.1 \times 10^{18} \text{ cm}$ ) and are associated with strong emission lines. Their power outputs are dramatically enormous ( $\sim 10^{46} \text{ ergs s}^{-1}$ ) and equal the mass - energy equivalent to several solar masses per year [3]. The nucleus of such galaxies are named "Active Galactic Nuclei"(AGN).

<sup>2</sup>Microquasars are stellar-mass black holes in our galaxy which mimic, in a smaller scale, of the phenomena seen in quasars. Unlike the AGN and Quasar jets (where the extend of the jets may reach several million of light years), the double sided jets coming out of these objects can have sizes upto a few light years only[4]

sources, one sees that in 1953, Jenison and Dasgupta [5] discovered that the radio emission from Cygnus A was originating from two amorphous blobs straddling symmetrically the associated optical galaxy rather than the galaxy itself (Figure 1.). Subsequent observations of other powerful radio emitting sources revealed the fact that this is rather a general phenomenon. Initially it was thought that these radio emitting blobs had been directly shot out of the core of the galaxy, however, this idea created some dynamical problems (adiabatic loss problem, as for example, see [3] for detail) which prompted theoreticians to propose a “black box model” to explain the phenomenon. In early theoretical contributions, what people put forward was basically a black box sitting at the dynamical center of the galaxy which is doing something interesting so that these radio emitting lobes are continuously fueled by the process of channeling matter and energy emanating from the galactic center. There is need to go into the history of subsequent discussion (and there is no scope to do so either due to the limitation of space, interested readers may have a look to [3] and [6-7]), suffice it to say that from the present status of observational evidences [8], we are in a strong position to say that these channels of matter and energy, or jets (as it was first named by Baade and Minkowski in 1954 [9]) are the ubiquitous feature of the AGNs, Young Stellar Objects (YSOs) and of some small scale prototype of AGNs, SS433 for example, which is believed to harbour a neutron star at its center. (For a detail discussion of SS433 jet, see [10-11]). Although since the first theoretical contribution to this black box model approach [12], much work has been done on how such jets interact with their surrounding and on how such interaction may convey the informations about the morphology of different extragalactic radio sources, the fundamental problem of what *exactly* is happening inside the black box still remains unresolved.

From the observational point of view, probably the most attractive feature of these astrophysical jets is that they are the most prominent and visible signatures of the AGNs. Hence, studying the jets has been one of the most exhaustive part of the research carried out by the observational astrophysicists over many years, and a huge “zoo” of different jet species has emerged.

On the other hand, from the theoretical front, the non-stellar activities around the AGNs are thought to be produced by a powerful engine sitting at the dynamical center of the galaxy [13]. Because of the fact that the high luminosity produced by the AGNs are concentrated in a very small volume, it has been strongly argued that these engines are basically powered by the accretion onto massive black holes. This “black hole hypothesis”, namely that essentially all AGNs contain  $\sim 10^6 - 10^9 M_\odot$  black holes [13-14] and that these objects together with their orbiting accretion disks are the prime movers for most of the powerful activities of AGNs including the formation of bipolar outflows and relativistic jets [15] are further supported by the recent observational evidences, specially from the VLBI observations and the HST data

where the signature of the so called “jet disk symbiosis” is supposed to be detected [16]. That means, for most (if not all) AGNs and microquasars, the jets and the accretion disks around the central compact object are symbiotically related [17]. Probably this has to be the case in reality because in the absence of any binary companion, jet is supposed to be the only outlet for the intrinsic angular momentum of the interstellar/ intergalactic matter accreting onto an isolated compact object [18]. So the accretion powered outflows are not merely an incidental by-product of the mass flow through the disk but, in fact, are a necessary ingredient in the accretion process, in that they constitute the main mechanism for removing excess angular momentum of the inflowing matter. Hence, it is quite logical to conclude that the jet formation and accretion onto isolated black holes are not two different issues to be studied disjointedly, but they must be strongly correlated and it is *necessary* to study the accretion and jet within the same framework. On the other hand, the major difference between the ordinary stellar outflows and the outflows/jets from the vicinity of a black hole or a neutron star, is that they do not have their own atmospheres and outflows/jets in this case have to be generated from the inflowing materials only.

Keeping these basic facts in the back of our mind, our aim was to theoretically study the mass outflow from galactic/ extragalactic sources more realistically than what has been attempted so far. The existing models which study the origin, acceleration and collimation of mass outflow in the form of jets from AGNs and Quasars are roughly of three types. The first type of solutions confine themselves to the jet properties only, completely decoupled from the internal properties of accretion disks [18-20]. In the second type, efforts are made to correlate the internal disk structure with that of the outflow using hydrodynamic, magnetohydrodynamic or electromagnetic considerations ([17] and references therein, [21-24]). In the third type, numerical simulations are carried out to actually see how matter is deflected from the equatorial plane towards the axis [25-31]. From the analytical front, though the wind type and accretion type solutions come out from the same set of governing equations [18-19], till today there was no attempt to obtain the estimation of outflow rate from the inflow rate. A theoretical model has very recently been developed [32-40], which, for the first time we believe, can compute (semi analytically and semi numerically) the absolute value of mass outflow rate from the matter accreting onto galactic and extra-galactic black holes using combinations of exact transonic accretion and wind topologies which form a self-consistent inflow-outflow system. The simplicity of black holes and neutron stars lie in the fact that they do not have atmospheres. But the inflowing matter surrounding them have, and similar method as employed in stellar atmospheres should be applicable to the accreting matter surrounding them. The approach in our model is precisely this. We first determine the properties of the rotating inflow and outflow and identify solutions to connect them. In this manner we

self-consistently determine what fraction of the matter accreting onto these compact objects is coming out as outflows/jets.

If  $\dot{M}_{in}$  is the time rate of accretion onto a compact object (the amount of matter *falling in* per unit time) and  $\dot{M}_{out}$  be the time rate of outflow (the amount of matter being 'kicked out' per unit time as *wind*), the ratio  $\left(\frac{\dot{M}_{out}}{\dot{M}_{in}}\right)$  we call the 'Mass Outflow Rate' and denote it by  $R_{\dot{m}}$ . Thus  $R_{\dot{m}}$  is a measure of the ratio of the outflow rate to the inflow rate of matter. The major aim of our work is to compute the absolute value of  $R_{\dot{m}}$  in terms of the inflow parameters and to study the dependence of  $R_{\dot{m}}$  on those parameters. Computation has been carried out for a Schwarzschild black hole using Paczynski-Wiita [41] pseudo-Newtonian potential which mimics the Schwarzschild space-time in an excellent fashion. For matter accreting with considerable intrinsic angular momentum (formation of accretion disks), we establish [32-33,36] that the bulk of the outflow is from the CENTrifugal pressure dominated BOundary Layer (it is called CENBOL, the formation of which will be explained in the next section), we find that  $R_{\dot{m}}$  varies anywhere from a few percent to even close to a hundred percent depending on the initial parameters of the inflow, the degree of compression of matter near the CENBOL and the polytropic index of the flow. Our model thus, not only provides a sufficiently plausible estimation of  $R_{\dot{m}}$ , but is also able to study the variation of this rate as a function of various parameters governing the flow [33, 36]. We have also studied the mass outflow from spherical accretion with zero intrinsic angular momentum [37-40]. It has been shown that a self-supported spherical pair-plasma mediated standing shock may be produced even for accretion with zero angular momentum. We have taken this shock surface as the generating surface of mass outflow for spherical inflow and have compared the results with that of obtained from the outflows generating from CENBOL (disk-outflow system). The plan of this article is as follows:

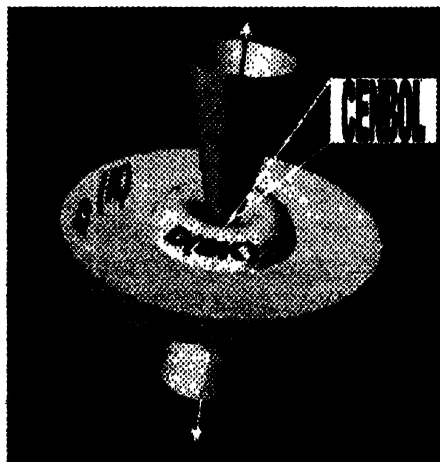
In the next section we describe our model for matter accreting with considerable angular momentum (formation of accretion disks) and present the results obtained for the disk-outflow system along with the solution scheme. In §3, we present how we model the inflow-outflow system for zero angular quasi-spherical accretion. Finally, in §4, we discuss some of the possible extensions of our work.

## 2. Disk-Outflow System:

### 2.1. Formation of CENBOL and the Outflow Geometry

Before we proceed further, let us describe basic properties of the rotating inflow and outflow. A rotating inflow with a specific angular momentum (angular momentum per unit mass) entering into a black hole will have almost constant angular momentum close to the black hole for any moderate viscous stress. This is because the viscous time scale to transport angular momentum

is generally much longer compared to the infall time scale (because near the black hole, the flow ‘advects’ inward with enormously large radial velocity) and even though at the outer edges the angular momentum distribution may be Keplerian or even super-Keplerian, matter would be highly sub-Keplerian close to the black hole. This happens because the flow *has to enter* through the horizon with velocity of light and presence of this large inertial (ram) force, in addition to usual gravitational and centrifugal forces, makes the flow sub-Keplerian. This almost constant angular momentum produces a very strong centrifugal force which increases much faster compared to the gravitational force (because while the centrifugal force varies inversely with the *cubic* power of the radial distance measured from the central gravitating body, gravitational attraction falls off obeying standard inverse square rule as usual *because we are using pseudo-Newtonian geometry instead of fully general relativistic treatment*) and becomes comparable at some specific radial distance, location of which is easy to compute. Here, (actually, a little farther out, due to thermal pressure) matter starts piling up and produces the centrifugal pressure supported boundary layer (CENBOL). Closer to the black hole, the gravity always wins and matter enters the horizon supersonically after passing through a sonic point. CENBOL may or may not have a sharp boundary, depending on whether standing shocks form or not. Generally speaking, in a polytropic flow, if the polytropic index  $\gamma > 1.5$ , then shocks do not form and if  $\gamma < 1.5$ , only a region of the parameter space forms the shock [42]. In any case, the CENBOL forms. In this region, the flow becomes hotter and denser (matter is either ‘shock-compressed’ or compressed by the maximization of polytropic pressure of the inflow) and for all practical purposes behaves as the stellar atmosphere so far as the formation of outflows are concerned. Inflows on neutron stars behave similarly, except that the ‘hard-surface’ inner boundary condition dictates that the flow remains subsonic between the CENBOL and the surface rather than becoming supersonic as in the case of a black hole [43].



**Figure 2:** Geometry of the disk-jet system

In case where the shock does not form, regions around pressure maximum achieved just outside the inner sonic point of the *inflow* would also drive the flow outwards. In the back of our mind, we have kind of picture of the outflow namely that the outflow is thermally and centrifugally accelerated but confined by external pressure of the ambient medium. Outflow rates from accretion disks around black holes and neutron stars must be related to the properties of CENBOL which in turn, depend on the inflow parameters. Subsonic outflows originating from CENBOL would pass through sonic points and reach far distances as in wind solution. Figure. 2 represents a schematic diagram showing the geometry of the disk-jet system proposed in our model. The arrows show the axis of the whirling jet, D(K) stands for the Keplerian part of the disk and D(SK) stands for the sub-Keplerian part. CENBOL forms somewhere inside the D(SK) and J stands for the hollow conical jet structure. There are two surfaces of utmost importance in flows with angular momentum. One is the ‘funnel wall’ where the effective potential (sum of gravitational potential and the specific rotational energy) vanishes. In the case of a purely rotating flow, this is the ‘zero pressure’ surface. Flows *cannot* enter inside the funnel wall because the pressure would be negative. (Fig. 3) The other surface is called the ‘centrifugal barrier’. This is the surface where the radial pressure gradient of a purely rotating flow vanishes and is located *outside* the funnel wall simply because the flow pressure is higher than zero on this surface. Flow with inertial pressure easily crosses this ‘barrier’ and either enters into a black hole or flows out as winds depending on its initial parameters (detail classification of the parameter space is in [31]). In our model the outflow generally hugs the ‘funnel wall’ and goes out in between these two surfaces (see [28, 33, 36] for detail).

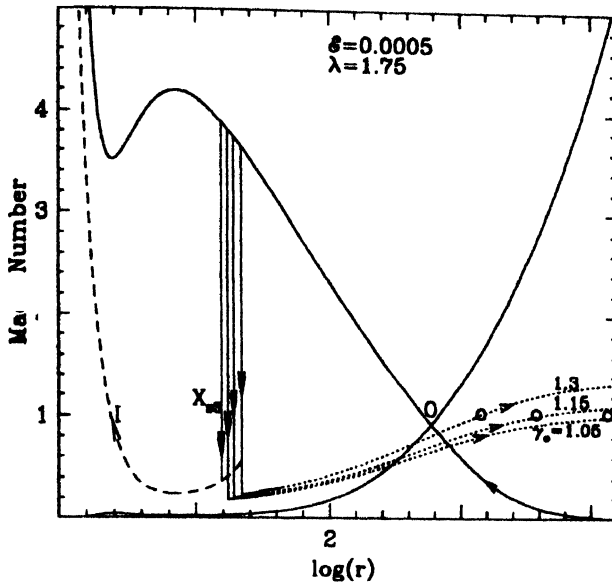
## 2.2. Model description, solution procedure and results

### 2.2.1. Model Description

We consider thin, axisymmetric polytropic inflows in vertical equilibrium (otherwise known as 1.5 dimensional flow [43]). We ignore the self-gravity of the flow and viscosity is assumed to be significant only at the shock so that entropy is generated. We do the calculations using Paczyński-Wiita [41] potential which mimics surroundings of the Schwarzschild black hole. Considering the inflow to be polytropic, we explore both the polytropic and the isothermal outflow. For polytropic outflows, the specific energy  $\mathcal{E}$  is assumed to remain fixed throughout the flow trajectory as it moves from the disk to the jet. At the shock, entropy is generated and hence the outflow is of higher entropy for the same specific energy. For isothermal outflow, we assume that the outflow has exactly the *same* temperature as that of the post-shock flow, but the energy is not conserved as matter goes from disk to the jet. In other words the outflow is kept in a thermal bath of temperature as that of the post-shock flow. The temperature of the outflow is obtained from the proton temperature







**Figure 4.** Few typical solutions which combine accretion and outflow. (Adopted from [36])

complete self-consistent solution boils down to finding the outer sonic point of the outflow and the mass flux through it [33, 36]. For polytropic outflows, the specific energy  $\mathcal{E}$  is assumed to remain fixed throughout the flow trajectory as it moves from the disk to the jet. At the shock, entropy is generated and hence the outflow is of higher entropy for the same specific energy. A supply of parameters  $\mathcal{E}$  (specific energy of the inflow),  $\lambda$  (specific angular momentum of the inflow),  $\gamma$  (polytropic index of the inflow) and  $\gamma_0$  (polytropic index of the outflow) makes a self-consistent computation of  $R_{in}$  possible (see [33, 36] for detail). All the physical quantities are measured in the Geometric Unit. It is to be noted that when the outflows are produced, one cannot use the usual Rankine-Hugoniot relations at the shock location, since mass flux is no longer conserved in accretion, but part of it is lost in the outflow. Accordingly, we modified the standard Rankine-Hugoniot condition [36].

### 2.2.3. Results

By simultaneously solving the proper set of equations in appropriate geometry (see [33, 36] for detail), we get the *combined* flow topologies which is presented as Figure 4. It shows a typical solution which combines the accretion and the outflow. Mach number (the ratio of the mechanical to the thermal velocity of matter) is plotted along the ordinate while the distance measured

from the central object (scaled in the unit of Schwarzschild radius) is plotted in logarithmic scale along abscissa. The input parameters are  $\mathcal{E} = 0.0005$ ,  $\lambda = 1.75$  and  $\gamma = 4/3$  corresponding to relativistic inflow. The solid curve with an incoming arrow represents the pre-shock region of the inflow and the long-dashed curve with an arrow inward represents the post-shock inflow which enters the black hole after passing through the inner sonic point (I). The solid vertical line at  $X_{s3}$  (the leftmost vertical transition) with double arrow represents the shock transition obtained with exact Rankine-Hugoniot condition (i.e., with no mass loss). The actual shock location obtained with modified Rankine-Hugoniot condition [36] is farther out from the original location  $X_{s3}$ . Three vertical lines connected with the corresponding dotted curves represent three outflow solutions for the parameters  $\gamma_o = 1.3$  (top), 1.15 (middle) and 1.05 (bottom). The outflow branches shown pass through the corresponding sonic points. It is evident from the figure that the outflow moves along solution curves completely different from that of the 'wind solution' of the inflow which passes through the outer sonic point 'O'. The leftmost shock transition ( $X_{s3}$ ) is obtained from unmodified Rankine-Hugoniot condition, while the other transitions are obtained when the mass-outflow is taken into account. The mass loss ratio  $R_{\dot{m}}$  in these cases are 0.256, 0.159 and 0.085 respectively. We can summarize the results of our calculation as follows:

- a) It is possible that most of the outflows are coming from the centrifugally supported boundary layer (CENBOL) of the accretion disks.
- b) The outflow rate generally increases with the proton temperature of CENBOL. In other words, winds are, at least partially, thermally driven. This is reflected more strongly when the outflow is isothermal.
- c) Even though specific angular momentum of the flow increases the size of the CENBOL, and one would have expected a higher mass flux in the wind, we find that the rate of the outflow is actually anti-correlated with the  $\lambda$  of the inflow. On the other hand, if the angular momentum of the outflow is reduced by hand, we find that the rate of the outflow is correlated with  $\lambda$  of the outflow. This suggests that the outflow is partially centrifugally driven as well.
- d) The ratio  $R_{\dot{m}}$  is generally anti-correlated with the inflow accretion rate. That is, disks of lower luminosity would produce higher  $R_{\dot{m}}$ .
- e) Generally speaking, supersonic region of the inflow do not have pressure maxima. Thus, outflows emerge from the subsonic region of the inflow, whether the shock actually forms or not. If we introduce an extra radiation pressure term (with a term like  $\Gamma/r^2$  in the radial force equation, where  $\Gamma$  is the contribution due to radiative process), particularly important for neutron stars, the outcome is significant. In the inflow, outward radiation pressure weakens gravity and thus the shock is located farther out. The temperature is cooler and therefore the outflow rate is lower. If the term is introduced only in the outflow, the effect is not significant [36]. However, we understand that inclusion of only  $\frac{\Gamma}{r^2}$  term does not give the whole picture of the various radiative processes taking place

in the disk-jet system and a more general and exact form of the radiative force term is to be included in the set of equations governing the inflow-outflow system.

An interesting situation arises when the polytropic index of the outflow is large and the compression ratio of the flow is also very high. In this case, the flow virtually bounces back as the winds and the outflow rate can be equal to the inflow rate or even higher, thereby evacuating the disk. In this range of parameters, most, if not all, of our assumptions may breakdown completely because the situation could become inherently time-dependent. It is possible that some of the black hole systems, including that in our own galactic center, may have undergone such evacuation phase in the past and gone into quiescent phase (see [33-36] for detail).

Strong winds are suspected to be present in Sgr A\* at our galactic center [45-46]. We have shown that when the inflow rate itself is low (as in the case for Sgr A\*;  $\sim 10^{-3} - 10^{-4}$  Eddington rate), the mass outflow rate is very high, almost to the point of evacuating the disk. This prompted us to strongly speculate that the spectral properties of our galactic center could be explained by inclusion of winds using our model [20].

### 3. Outflow from Bondi type accretion

#### 3.1. In search for a suitable surface

For some black hole models of active galactic nuclei, inflow may not have accretion disk [47]. Accretion is then quasi-spherical having almost zero or negligible angular momentum (Bondi [48] type accretion). Absence of angular momentum rules out the possibility of formation of the Rankine-Hugoniot shock as well as the polytropic pressure maxima. So, for quasi-spherical accretion, the process CENBOL formation (as discussed in the earlier section) is not possible. It has been shown that [49-50] for quasi-spherical accretion onto black holes, steady state situation may be developed close to the black hole where a standing collisionless shock may form due to the plasma instabilities and for nonlinearity introduced by small density perturbation. This is because, after crossing the sonic point the infalling matter (in plasma form) becomes highly supersonic. Any small perturbation and slowing down of the infall velocity will create a piston and produce a shock. A spherically symmetric shock produced in such a way will accelerate a fraction of the inflowing plasma to relativistic energies. The shock accelerated relativistic particles suffer essentially no Compton loss and are assumed to lose energy only through proton - proton ( $p-p$ ) collision. These relativistic hadrons are not readily captured by the black hole [51] rather considerable high energy density of these relativistic protons would be maintained to support a standing, collisionless, spherical shock around the black hole [50]. Thus, a self-supported standing shock may be produced even for accretion with zero angular momentum. In this work, we

take this pair-plasma pressure mediated shock surface as the alternative of the CENBOL which can be treated as the *effective* physical hard surface which, in principle mimics the ordinary stellar surface regarding the mass outflow.

The condition necessary for the development and maintenance of such a self-supported spherical shock is satisfied for the high Mach number solutions [52] Keeping this in the back of our mind, for our present work, we concentrate only on low energy accretion to obtain high shock Mach number. Considering low energy ( $\mathcal{E} \lesssim 0.001$ ) accretion, we assume that particles accreting toward black hole are shock accelerated via first order Fermi acceleration producing relativistic protons. Those relativistic protons usually being scattered several times before being captured by the black hole. These energized particles, in turn, provide sufficiently outward pressure to support a standing, collisionless shock. A fraction of the energy flux of infalling matter is assumed to be converted into radiation at the shock standoff distance through hadronic ( $p - p$ ) collision and mesonic ( $\pi^\pm, \pi^0$ ) decay. Pions generated by this process, decay into relativistic electrons, neutrinos/antineutrinos and produces high energy  $\gamma$  rays (see [38] for details). These electrons produce the observed non-thermal radiation by Synchrotron and inverse Compton scattering. The overall efficiency of this mechanism depends largely on the shock location. Luminosity produced by this fraction is used to obtain the shock location for the present work.

### 3.2. At the end of the search

At the shock surface, density of the post-shock material shoots up and velocity falls down, infalling matter starts piling up on the shock surface. The post shock relativistic hadronic pressure then gives a kick to the piled up matter the result of which is the ejection of outflow from the shock surface. For this type of inflow, accretion is known to proceed smoothly after a shock transition, since successful subsonic solutions have been constructed for accretion onto black holes embedded within normal stars with the boundary condition  $u = c$ ; where  $u$  is the infall velocity of matter and  $c$  is the velocity of light in vacuum. The fraction of energy converted, the shock compression ratio  $R_{comp}$ , along with the ratio of post shock relativistic hadronic pressure to infalling ram pressure at a given shock location are obtained from the steady state shock solution of Ellison and Eichler [52-53]. The shock location as a function of the specific energy  $\mathcal{E}$  of the infalling matter and accretion rate is then self-consistently obtained using the above mentioned quantities. We then calculate the amount of mass outflow rate  $R_{\dot{m}}$  from the shock surface using combination of exact transonic inflow outflow solutions and study the dependence of  $R_{\dot{m}}$  on various physical entities governing the inflow-outflow system [38].

### 3.3. Model description, solution procedure and results

#### 3.3.1. Model description and solution procedure

We assume that a Schwarzschild type black hole quasi-spherically accretes low energy ( $\mathcal{E} \lesssim 0.001$ ) fluid obeying polytropic equation of state. We also assume that the accretion rate (in the unit of Eddington rate) with which the fluid is being accreted, is not a function of  $r$  ( $r$  being the radial distance measured from the central object scaled in the unit of Schwarzschild radius). For simplicity of calculation, we choose geometric unit to measure all the relevant quantities. We ignore the self-gravity of the flow and the calculation is being done using Paczynski-Wiita [41] potential which mimics surrounding of the Schwarzschild black hole. As already mentioned, we assume that a steady, collisionless shock forms at a particular distance (measured in the unit of Schwarzschild radius) due to the instabilities in the plasma flow. We also assume that for our model, the effective thickness of the shock is small enough compared to the shock standoff distance. For simplicity of calculation, we assume that the outflow is also quasi-spherical.

It is obvious from the above discussion that  $R_{\dot{m}}$  should have some complicated functional dependences on the inflowing parameters through the shock location (see [38] for detail).

#### 3.3.2. Results

By simultaneously solving the proper set of equations in appropriate geometry (see [38] for detail), we get the *combined* flow topologies which is presented as Figure 5. It shows a typical solution which combines the accretion and the outflow. Mach number (the ratio of the mechanical to the thermal velocity of matter) is plotted along the ordinate while the distance measured from the central object (scaled in the unit of Schwarzschild radius) is plotted in logarithmic scale along abscissa. The input parameters are  $\mathcal{E} = 0.001$ ,  $\dot{M}_{in} = 1.0$  Eddington rate ( $\mathcal{E}_d$  stands for the Eddington rate in the figure) and  $\gamma = \frac{4}{3}$  corresponding to relativistic inflow. The solid curve with an arrow represents the pre-shock region of the inflow and the solid vertical line with double arrow at  $X_{pps}$  (the subscript *pps* stands for *pair plasma mediated shock*) represents the shock transition. Location of shock is obtained using the eqs.(4) for a particular set of inflow parameters mentioned above. Three dotted curves show the three different outflow branches corresponding to different polytropic index of the outflow as  $\gamma_o = 1.3$  (left most curve), 1.275 (middle curve) and 1.25 (rightmost curve). It is evident from the figure that the outflow moves along the solution curves completely different from that of the “wind solution” (solid line marked with an outward directed arrow) of the inflow which passes through the sonic point  $P_s$ . The mass loss ratio  $R_{\dot{m}}$  for these cases are 0.0023, 0.00065 and 0.00014 respectively.

We can summarize our results obtained in this case as follows:

1. It is possible that outflows for quasi-spherical Bondi type accretion onto a Schwarzschild black hole are coming from the pair plasma pressure mediated shock surface.
2. The outflow rate monotonically increases with the specific energy of the inflow and nonlinearly increases with the Eddington rate of the infalling matter.
3.  $R_{\dot{m}}$ , in general, correlates with  $\gamma_o$  but anticorrelates with  $\gamma$ .
4. Generally speaking, as our model deals with high shock Mach number (low energy accretion) solutions, outflows in our work always generate from the supersonic branch of the inflow, i.e, shock is always located *inside* the sonic point.
5. Unlike the mass outflow from the *accretion disks* around black holes [33,36] here we found [38] that the value of  $R_{\dot{m}}$  is distinguishably small. This is because matter is ejected out due to the pressure of the relativistic plasma pairs which is *very much less* in comparison to the pressure generated due to the presence of significant angular momentum. However, in the present work we have dealt only high Mach number solution which means matter is accreting with very low energy (cold inflow, as it is described in literature). This is another possible reason to obtain a low mass loss rate. If, instead of high Mach number solution, we would use low Mach number solution, e.g, high energy accretion, the mass outflow would be considerably higher (this is obvious because it has already been established in present work that  $R_{\dot{m}}$  increases with  $\mathcal{E}$  (see [38] for detail).

#### 4. Future perspectives

Based on the works have already been done, our goals for the future work are essentially the following:

1. We have carried out our calculations for the Schwarzschild black hole using Paczyn'ski-Wiita [41] pseudo-Newtonian potential. Now we would like to extend our calculations in fully general relativistic framework so that the parameter space for calculation gets modified and the mass-loss rate calculated in this way could be compared with our previous results.
2. In our work, we assumed that the magnetic field is absent. Magnetized winds from the accretion disks have so far been considered in the context of a Keplerian disk and not in the context of sub-Keplerian flows on which we concentrate here. It is not unreasonable to assume that our prime surface for the wind formation, the CENBOL would still form when magnetic fields are present and since the Alfvén speed is, by definition, higher compared to the sound speed, the acceleration would also be higher than what we computed here. Moreover, introduction of toroidal magnetic field in our model with its associated “hoop” stress, would lead to a better understanding of the “collimation problem” of the jets.

3. Recently it has been suggested ([54] & references therein) that significant nucleosynthesis is possible in the centrifugal pressure supported dense and hot region of the accretion flow which deviate from the disk around the black holes. Attempts had been made to compute the composition changes and energy generation due to such nuclear processes as a function of the radial distance from the black hole. We suggest that the outflows produced from this region would carry away modified composition and contaminate the atmosphere of the surrounding stars and the galaxies in general. Unlike the present calculation, where the outflow consists of  $m_p$  only (proton jet), now we will be trying to take the weighted average of the heavier elements produced by the nucleosynthesis in advective accretion disks as the constituent elements of the outflow.
4. Finally, we would like to carry out all of our calculations (done for Schwarzschild black hole) in Kerr space-time to bring the whole picture into focus.

## 5. Concluding remarks

It is to be noted that although the existence of astrophysical outflows and jets from the galactic and extragalactic sources are well known, their rates are not. Similarly, till date, there is no definitive model present in the literature which can handle the origin of this outflow in a self-consistent way. Hence we think that the formation and dynamics (acceleration and collimation) of these outflows are the open problems in present day theoretical astrophysics. Along with our present analysis of mass outflow in Schwarzschild geometry, if we can carry out our calculation in Kerr geometry as well, we strongly believe that these combined calculations definitely could shed some new light on the origin and energetics of the astrophysical jets.

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